Non Locality, Counterfactuals and the Quantum Theory — St. Andrews April 1981

I want to begin with two thought experiments.

1.) I stand at one end of a table – at the other end is a clock. At an instant before 9 p.m. I raise my hand and at the next instant the clock strikes.
Query: If I had not raised my hand would the clock have struck?

Answer: yes, other things being sufficiently the same, if the clock is not smashed with a hammer.

2.) the clock is replaced with an atom of radium, which emits an α-particle exactly at 9 p.m., an instant after I raise my hand.
Query: If I had not raised my hand would the α-particle have been emitted?

Answer: (Surprisingly!). We cannot in this case give a definite yes, the answer is rather 'perhaps' or 'possibly'.

But a number of influential physicists have claimed that the answer to the second question is also yes and have used this fact, if it is a fact, to show in a very general way that QM is a nonlocal theory.

If 1) or 2) were not answered in the affirmative then a violation of locality would result, an effect 'at a distance' of one macroscopic event i.e. raising my hand caused the clock to strike and the alarm to sound or the geiger-counter detecting the α-particle to register.

Thus if not raising my hand caused the clock not to strike then raising ~~would~~ my hand would appear to be a necessary condition for the clock to strike perhaps an Inus Condition in the terminology of Mackie (Inus = Insufficient but necessary part of unnecessary but sufficient condition).

In this paper I want to do two things

1.) Explain the rather subtle way in which the nonlocality is actually demonstrated

2.) To examine from the point of view of the philosophical analyses of counterfactuals what the correct answer to the second question should be.

Summary Version

The Quantum View of the World

1. In November 1979 Prof. d'Espagnat published an article in Scientific American with the title 'The Quantum Theory & Reality'. The subheading read as follows

Interaction of Science and Philosophy clearly evident here.

"The doctrine that the world is made up of objects whose existence is independent of human consciousness turns out to be in conflict with QM and with facts established by experiment".

– created a furore of reaction among physicists

What are these experiments etc.

2. Interaction of philosophical and scientific problems in the understanding of QM

also influence aspect.

Philosophy is study of and analysis of concepts, principles and ultimate presuppositions underlying of any branch of knowledge.

← Philo. of Physics   Physics →

Bohr example

−200   −2   +1 – – +200

Pages −1 – – −200 eg explain & discuss what is assumed on p. 1,

3. Minimal instrumentalist interpretation of QM.
But Einstein, Schrodinger, and indeed Bohr sought to provide a conceptual understanding of what was going on.

in QM – if you like a Quantum View of the World.

4. Uncertainty relations: cannot measure simultaneously non-commuting observables.

But. If you cannot measure something does this mean there is nothing there to be measured.

3 views. For an eigenstate of position
[illegible] does momentum have

QM not incomplete ← a) A sharp although unknown value. — hv theories, Einstein

QM incomplete new concepts ← b) An unsharp or 'fuzzy' value. — potentiality Landé etc., Margenau, Heisenberg

QM incomplete — inadequacy of ordinary concepts. ← c) Momentum is meaningless, i.e. undefined. — Bohr.

Does QM and in its empirical ~~for~~ aspects throw any light on these possibilities? — or is the whole discussion of such questions purely metaphysical?

If we now measure momentum what sort of ~~transition~~ change has occurred in reality?

a.) a pre-existing value has been revealed
b) a potential result has been actualized
c) an undefined or meaningless quantity has now become defined
d)

Has this change been brought about by interaction with a physical apparatus or by the action of human consciousness as suggested by d'Espagnat?

The EPR Argument (1935)

EPR showed that

QM + Locality, → Incompleteness.

using Sufficient Condition of Reality

If without disturbing a system we can predict with certainty the value of an observable then already, before the prediction, there exists an element of reality corresponding to that observable

and the Necessary Condition for Completeness

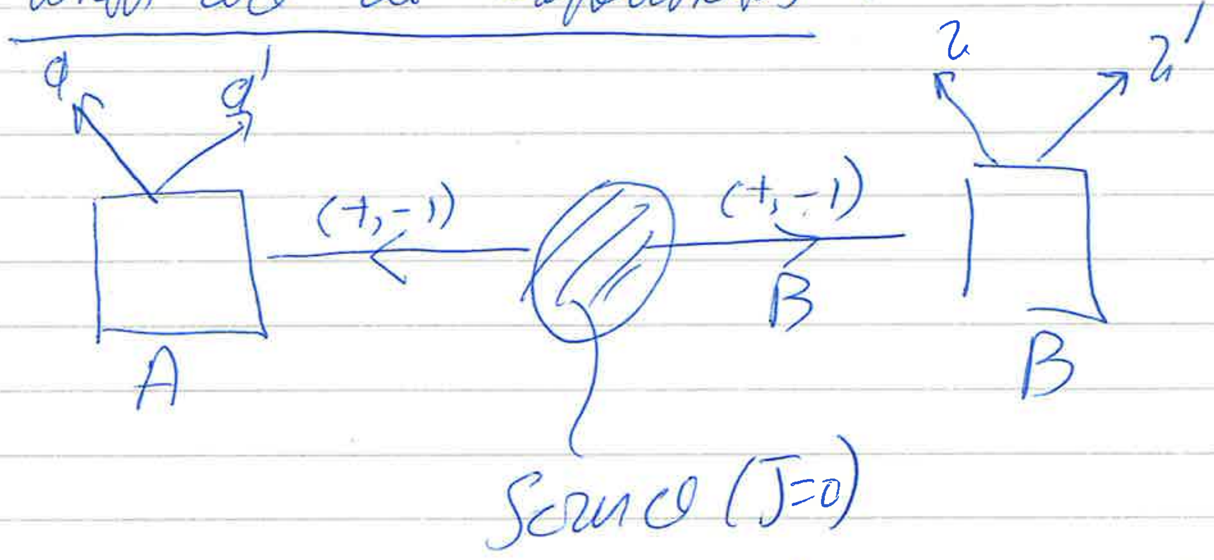
every element of reality has ~~an element~~ counterpart in the theory associated with it.

Hence QM → either Non-locality, or Incompleteness

This is the Einstein dilemma. (Bohr's response is to reject locality, ie locality$_2$). EPR took the second horn (the first horn leads to the so-called EPR Paradox)

But we shall see later ~~Inc~~ Completeness of QM → Nonlocality$_3$

5. What are the experiments?



a_n denotes spin-component of A-particle parallel to direction a for n^{th} pair of particles etc.

Form $\gamma_n = a_n b_n + a_n b'_n + a'_n b_n - a'_n b'_n$

$$\left(= a_n(b_n + b'_n) + a'_n(b_n - b'_n)\right)$$

So $\gamma_n = \pm 2$.

Now form $\left|\frac{1}{N}\sum_n \gamma_n\right| = \left|\frac{1}{N}\sum a_n b_n + \frac{1}{N}\sum a_n b'_n + \frac{1}{N}\sum a'_n b_n - \frac{1}{N}\sum a'_n b'_n\right|$

≤ 2

$$= \left|c(a,b) + c(a,b') + c(a',b) - c(a',b')\right| \le 2.$$

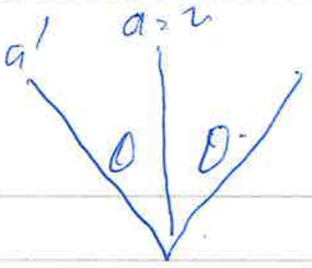
Where correlation coefficient

$$c(a,b) = \frac{1}{N}\sum a_n b_n = \overline{a_n b_n}$$

For QM $c(a,b) = -\cos\theta_{ab}$

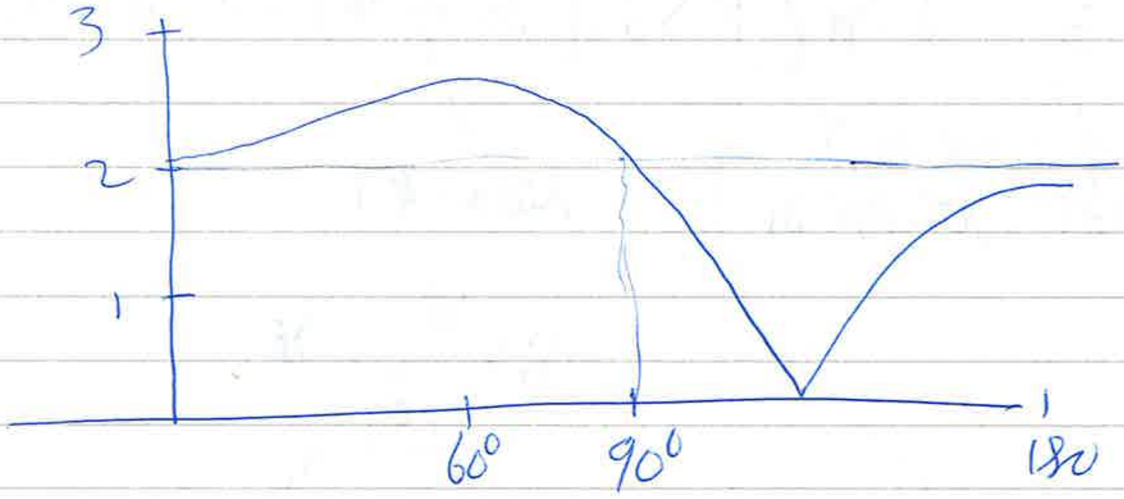
$$\simeq -1 + \frac{1}{2}\theta_{ab}^2$$

Take $a = b$



$$F(\theta) = | C(a,b) + \ldots - |$$

$$= | 1 + 2\cos\theta - \cos 2\theta |$$



~~For small θ $F(\theta$~~

For classical example.

$$C(a,b) = -1 + \frac{2\,\theta_{ab}}{\pi}$$

But we are assuming locality$_3$:

a sharp value cannot be changed into another sharp value by altering the setting of a remote piece of apparatus.

This may be taken in the Bell sense or in the ~~EA~~ weaker Einstein sense – no action at a space-like separation. (i.e. no instantaneous action at a distance)

– Distinguished by Aspect's experiment

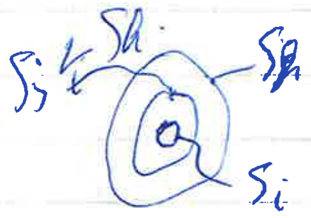
Analyses of Counterfactuals:

$\phi \Box\!\!\rightarrow \psi$

$$\equiv \quad \exists S_k \left(\forall S_j \left(\left(S_j \leq_i S_k \right) \to \left(\phi \to \psi \right) \right) \right)$$

ϕ is false in S_i
and true for some S_j

nearer to i



$$\neg \exists S_\ell \left(\left(S_\ell \leq_i S_k \right) \wedge \phi \text{ is true in } S_\ell \right)$$

i.e. $\exists S_k \left[\exists S_\ell \left(\left(S_\ell \leq_i S_k \right) \wedge \phi \text{ is true in } S_\ell \right) \wedge \forall S_j \left(\left(S_i \leq_i S_\ell \right) \to \left(\phi \to \psi \right) \right) \right]$

5

But suppose we are not dealing
with sharp values at all
Then can we give a

6. Counterfactual formulation of Stapp

○ Eberhard.

Principle of Local Counterfactual definiteness:
the result of an experiment which could be performed but is not has a definite value ~~independent~~ which does not depend on the setting of a remote piece of apparatus

This principle is extremely suspect in ~~an~~ a scheme of genuine indeterminism in respect to the outcome of a measurement.

E1
Actual experiment
A
A box
B of radium
- days
Counterfactual Experiment
World after days
?
Time t1
Time: t2 > t1

So we are not really entitled in denying Locality A:

Locality A: A macroscopic object cannot have its classical state altered by causes isolated by other macroscopic object as a space-like separation.

7. Let me reinforce the discussion of locality by considering the case where a, b are parallel and we get perfect anticorrelation. By measuring b_n we know that a_n is just $-b_n$.

Now consider the sequence of results recorded at A

+ − − + + − + − − −

Can we alter this sequence instantaneously — Violation of Locality[5]

Well at B we are really tagging the events as being registered at A, but to change the statistics at A e.g. to put a deflecting plate every time we predict a − result so the response at A now reads

+ + + + + +

But the tagging information is at the wrong place. We must get it back from B to A to achieve any change in statistics.

Ex room in Chelsea empty as I arrive at I.C. but to change the physical situation at Chelsea, to prevent students knocking on my door, would involve getting the information back to Chelsea.

8. ~~What about violating locality$_1$? An unsharp value cannot be turned into a sharp value by space-like separation. This principle is denied by the anticorrelation experiment described.~~

~~but should we really be talking about~~

~~locality$_2$ An undefined value cannot be defined by measurements performed ~~at~~ with a remote apparatus.~~

~~The denial of this principle is essentially Bohr's response to these experiments. But is this formulation really consistent with realism.~~

If we want to preserve realism we must give up locality, or locality$_3$.

Q. Would this conflict with S.R. cf Tachyon causal theory of time, causal loop paradoxes etc.! — Aspect's experiment.

Finally what about the human mind. Does the fact that we can alter things at a distance mean that what happens at a distance depends on our intentions. Well no more than saying that if I kick a stone the motion of the stone can ultimately be traced back to my intention to move my leg.

But suppose I fall out of bed and touched a stone with my foot. Then the motion of the stone can hardly be said to depend *necessarily* on my consciousness or my will. The same sort of asymmetry is going on at level of Experiment. ~~If the probe 2 moves as a result of human intention then indeed we might~~ Measurements are certain sorts of physical interaction – the fact that we *design* the experiments or register the results in our consciousness does not seem to me make the *existence* of the external world depend on such consciousness.

9. So with some form of non-locality we can retain realism. But can we? There is another difficulty associated with the so-called Kochen-Specker paradox (1967)

They showed:

QM + Completion + Func. → contradiction

But feature of QM involved is

Corr: observables & operators are in 1:1 correspondence.

We can retain completion only by forsaking Corr.

In fact Corr. → Func. (effectively) so giving up Func. → giving up Corr.

The K-S paradox replaces the 1:1 mapping by a many-one mapping in respect of degenerate operators (so more eigenvalues the same)

Then de Ockhamized version of QM is due to Van Fraassen (1973)

N.B. The Bell theorem employs not ~~full~~ unrestricted Corr. but the statistical Algorithm of QM, so it really says:

Stat. Algorithm + completion (+ requisite determinism) + locality$_3$ → contradiction.

Note also that having dealt with K-S and Bell non-locality problems we still may not be able to find a full hidden-variable phase-space reconstruction of QM due to the no-joint distribution proofs of Cohen and Nelson, using of a weak form of Fine. which does not involve K-S paradoxes.

Thus Cohen (1966) uses $f(Q) \equiv Q^2$ while Nelson (1967) uses $f(Q_1, Q_2) = x_1 Q_1 + x_2 Q_2$ but there are in general derived from assumptions about non-commuting observables (since $Q = f(p, q)$ for Cohen eg.) so they are not really weaker assumptions than K-S. Indeed Nelson is equivalent to von N. additivity assumption cf. also Moyal (1949)

$$\frac{p^2}{2m} + \frac{1}{2} k q^2$$

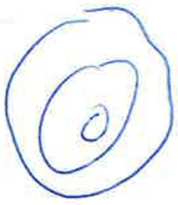
$E_n = (n + \frac{1}{2}) \hbar \omega$, $\omega = \sqrt{k/m}$

Take $m = \frac{1}{2}$, $k = 2$, $\omega = 2$

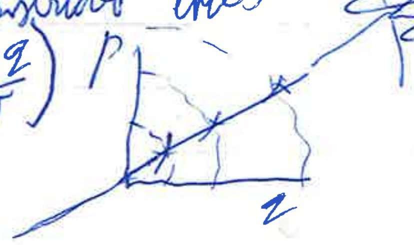
$E_n = (2n+1)\hbar$, (p, q) must be distributed on discrete circles in phase-space – contradicts e.g. joint distributions derived from time of flight measurement example (Park & Margenau 1968). Two ways out, a) H is not represented by $\frac{p^2}{2m} + \frac{1}{2} k q^2$ or b) (p, q) do not have a joint distribution – cf Fine.

$$\text{Prob}(p = a, q = x) = |\psi(x)|^2 \cdot \delta\left(a - \frac{mx}{T}\right)$$

So p, q, are distributed thus instead of



$\text{Prob}(p, q) = |\psi(q)|^2 \cdot \delta\left(p - \frac{mq}{T}\right)$



10. The Connection with the EPR Argument (1935)

QM + locality$_1$ → incompleteness.

Bohr's response was to claim that locality$_2$ was involved which could be given up

$$\left[\text{cf } A \wedge B \to C \equiv A \to (B \to C) \equiv A \to (\neg B) \vee C \equiv B \to (\neg A) \vee C \right]$$

~~If we block~~

So QM → non-locality$_1$ ∨ (Incompleteness)

but both horns lead to non-locality.

Since Completion → non-locality$_3$ (cf also von Neumann 1932).

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11. Interaction of Physics and Philosophy

Either

1.) Physics should be changed in the light of philosophical preconceptions

or 2.) Philosophical ideas should be modified in the light of new theories of physics.

are these really 'philosophical'

I am tempted myself to subscribe to the latter option, even if this downgrades the status of the philosopher vis à vis the physicist.

However* In the case of Einstein's Relativity relativeness ~~[illegible]~~ fails to exploit his philosophy while both seem as a very unclear mish-mash of Kierkegaard and Kant, to mention some of his sources

The role of philosophy is to promote understanding of what physics really *is* — commentary as to.

Of course theoretical physicists *do* use philosophical analysis as a part in their work — Einstein & Bohr are notable examples.* But the surprising thing is that muddled philosophy is quite consistent with splendid physics. In a sense one could claim that Einstein did not *understand* relativity nor Bohr quantum mechanics, but then one can *do* physics without understanding it rather like riding a bicycle without knowing anything about rigid-body dynamics. (With that deliberately provocating remark I will bring this talk to a close.)

But how much better to *do* physics and understand it — to *combine* the study of physics with the study of the philosophy of physics.